Solar energy in western Rajasthan

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This article reviews the state-of-the-art for generating electricity from solar energy, through the photovoltaic and thermal routes. On the whole, India has made significant efforts for the successful utilization of solar energy. A large number of kilowatt scale PV power packs and systems for a variety of applications have been installed. Successful attempts have also been made to integrate a few PV systems with the grid. As regards the thermal route, the experience of generating electricity has been limited. However, ambitious plans are afoot for setting up a few large power plants in western Rajasthan where the conditions are most appropriate for the utilization of solar energy.

ENERGY from the sun sustains life on our earth. It is also the source of almost all forms of energy used by man. Fossil fuels such as coal, oil and natural gas represent solar energy that was received on earth millions of years ago, while renewable sources of energy like wind, hydroelectric power, biomass and ocean energy are indirect forms of solar energy.

Solar energy, as received directly, can be used in a number of ways and for many applications. The two routes for utilization are the thermal route using the heat for heating, cooling, drying, water purification, power generation, etc. and the photovoltaic route which converts the light into electricity which can then be used for a variety of purposes such as lighting, pumping, communication and refrigeration. In this article, we focus on various technologies and systems using solar energy directly for generating electricity.

India receives solar energy equivalent to over 5000 trillion kWh/year which is many times more than the total energy consumption of the country. The daily average incident solar energy varies from 4 to 7 kWh/m^2 depending upon the location and there are 250–300 sunny days in most parts of the country. The potential for using solar energy to meet the growing energy needs of the country was recognized in the mid seventies. Research and development efforts in both solar thermal and photovoltaic routes were initiated. Several applications were developed and demonstrated during the eighties. These efforts received an impetus with the establishment of the Ministry of Non-Conventional Energy Sources (MNES) in 1992. The Ministry's programmes include R&D, demonstration, commercialization and utilization activities in respect of a wide variety of renewable energy technologies. The programmes are implemented through a network of state level agencies, industrial, research and academic organizations and non-governmental bodies. As a result of these efforts, India today has one of the world's largest programmes in solar energy. Solar energy is beginning to be used for a large number of applications. Nevertheless, the achievements so far add up to only a tiny fraction of what is possible. The efforts initiated during the last three years by MNES to restructure the programmes and give them a market orientation could lead to a significant acceleration in the utilization of solar energy in the country.

Availability of solar radiation over western Rajasthan

Rajasthan is the second largest state in size in the country, covering about 10.4% of the land area. The state has limited traditional sources of energy. It has only two perennial rivers, the Chambal and the Mahi, whose hydroelectric potential has been almost fully exploited. There are no coal mines or oil fields. However, there are some gas and lignite reserves.

In order to discuss the potential for using solar energy in western Rajasthan, it is desirable to examine the climatic conditions of that region. The variables of importance from the point of view of generating solar electricity, are solar radiation, sunshine hours, clearness index and ambient temperature.

Western Rajasthan experiences a hot and dry climate with a severe summer, relatively clear skies, a short monsoon period and a cold winter. Table 1 presents annual and monthly averages of daily values of global solar radiation, sunshine hours and clearness index for four towns of the region. In order to get a comprehensive picture of the spatial distribution of these quantities over the whole area, a map showing the distribution of the annual mean daily global solar radiation and the clearness index is presented in Figure 1. It is seen that the solar insolation level is high. In fact, the values over western Rajasthan are the highest for the whole country. Further, the sunshine hours and values of clearness index for the region are consistently high, except for a short monsoon period. This implies an excellent availability of beam radiation. Consequently solar devices which need concentration of radiation would perform much better in this region. Besides these factors, the ambient temperatures are high throughout the year touching more

Table 1. Global solar radiation (G in kWh/m^2 day), sunshine hours (S) and clearness index (K_T) in western Rajasthan[4,5]

Place	Parameter	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Barmer	G	4.69	5.62	6.57	7.47	8.06	7.89	6.55	6.26	6.62	6.07	5.07	4.47
	S	8.9	9.6	10.1	11.0	12.0	11.2	7.3	7.1	9.5	10.2	9.5	8.8
	K_T	0.72	0.72	0.72	0.72	0.73	0.70	0.59	0.59	0.69	0.73	0.73	0.72
Bikaner	G	4.46	5.37	6.38	7.49	8.12	8.15	7.29	6.83	6.79	5.96	4.80	4.21
	S	8.8	9.4	10.0	11.3	12.2	12.0	9.6	8.9	10.4	10.4	9.3	8.7
	K_T	0.72	0.71	0.71	0.73	0.74	0.72	0.65	0.65	0.71	0.74	0.73	0.72
Jaisalmer	G	4.61	5.56	6.49	7.48	8.11	8.24	7.44	7.08	6.81	6.06	5.00	4.36
	S	9.0	9.7	10.1	11.2	12.2	12.3	10.0	9.6	10.3	10.5	9.6	8.8
	K_T	0.72	0.73	0.71	0.73	0.74	0.73	0.67	0.67	0.71	0.74	0.74	0.72
Jodhpur	G	4.72	5.57	6.55	7.23	7.55	7.07	5.98	5.54	6.10	5.83	4.90	4.43
	S	9.1	9.7	8.9	10.0	10.6	9.5	6.7	6.2	7.7	9.5	9.7	9.2
	K_T	0.72	0.72	0.68	0.69	0.68	0.64	0.56	0.57	0.65	0.72	0.74	0.73

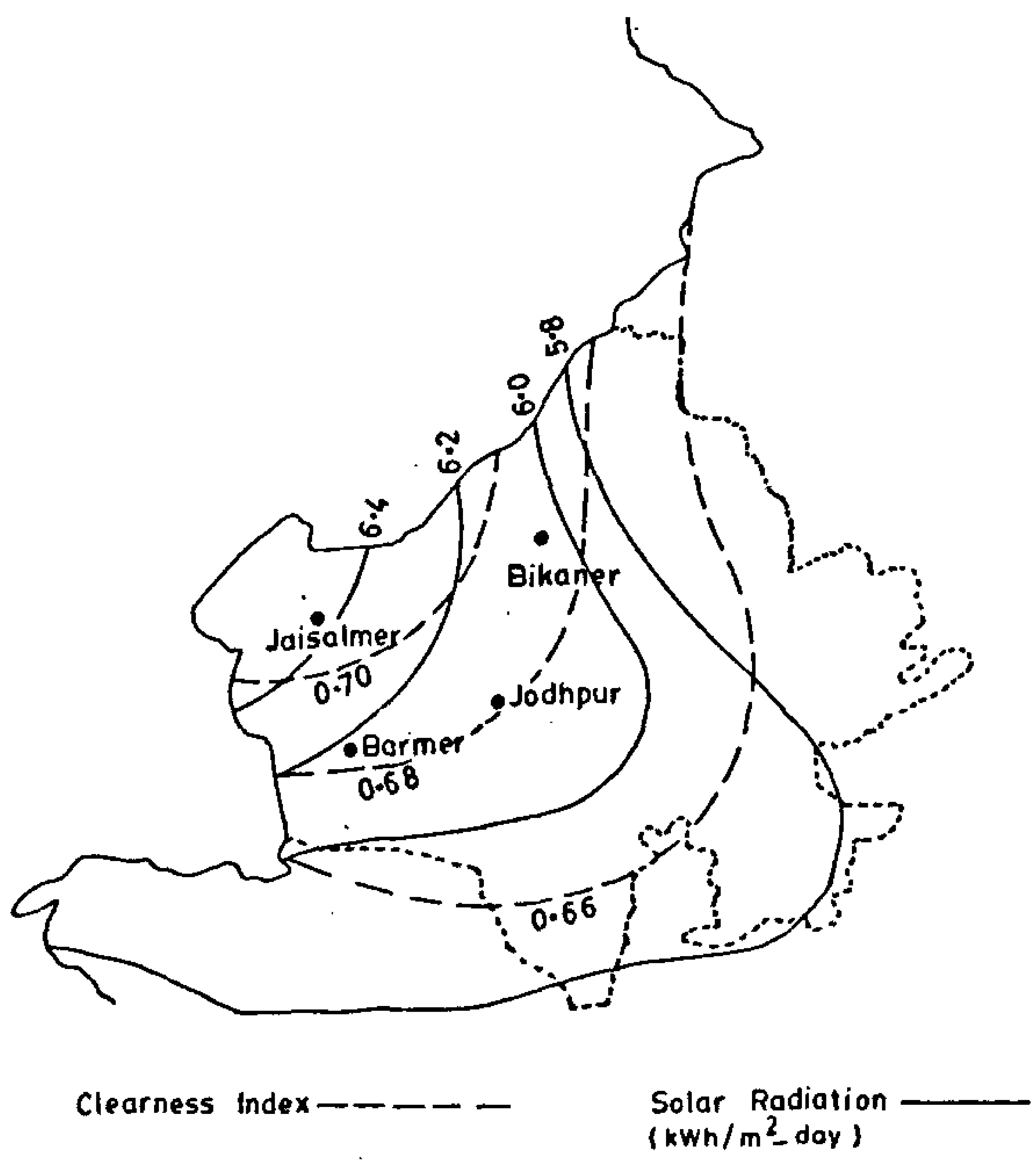

Figure 1. Distribution of annual mean daily global solar radiation and clearness index over western Rajasthan[5].

than 45°C during the summer. Thus the region is the best in the country from the point of view of utilizing solar energy.

Photovoltaic technology

Photovoltaic (PV) technology enables the direct conversion of sunlight into electricity. A photovoltaic module is the basic building block of a PV system. The power from the PV module can be used to run pumps, lights, refrigerators, TV sets, etc. The PV modules, batteries, charge controller, inverter (if any), mounting structure, cables, switches and the appliances being powered together constitute a complete PV system.

PV power systems have several advantages. They are modular in nature and have no moving parts, produce no noise or pollution and require very little maintenance. They can be installed almost anywhere, making them an ideal power source for use in remote and isolated areas which are not served by conventional electricity.

With 75,000 villages still to be electrified, there is a vast scope and potential for use of PV technology in India. Recognizing this fact, the government has been implementing a comprehensive programme covering R&D, demonstration, commercialization and utilization aspects for over 15 years. The technology for the fabrication of solar cells using single crystal silicon wafers has been developed and commercialized in the country based on indigenous efforts. This was followed by further demonstration of the applications in different sectors and the development of newer technologies such as amorphous silicon and other thin film technologies.

India has acquired a leading status among the countries of the world in the development and use of PV technology. The Indian market and programme are the largest among developing countries and India has emerged as the second largest manufacturer of PV modules based on crystalline silicon technology. Industrial production touched a level of 7 MW during 1995–96. There are over 75 companies now engaged in the production of solar cells, modules and systems. There are seven solar cell manufacturers and ten PV module manufacturers in production.

Some applications for which PV systems have been developed are:

1. Pumping water for irrigation and drinking.
2. Electrification for villages for providing street lighting and home lighting and for providing community services.

3. Telecommunication for the posts and telegraph and railway communication network, and for other specialized purposes.

A diagram of a typical system for pumping water from a bore well is shown in Figure 2. A solar cell array supplies power through a dc–ac inverter to an electric motor coupled to a submersible pump. The pump is installed below the water level of the bore well. Its discharge is connected through a delivery pipe to a storage tank at ground level. Water can be withdrawn from the storage tank for use when required. Usually systems for pumping water do not have storage batteries and work only during the day when adequate solar radiation is available. However, other PV systems which have to supply power during the evening or night have storage batteries to store the electrical energy generated during the day, the capacity of the battery being determined by the nature of the application.

Rajasthan is one of the leading states in the country in utilizing solar photovoltaic technology for decentralized and stand-alone systems. With assistance from the Central Government, the Rajasthan Energy Development Agency (REDA) has been implementing a programme for providing PV lighting systems in its rural and remote villages. Under this scheme the State has deployed 5545 street lighting systems, 4700 solar lanterns and 115 community TV systems.

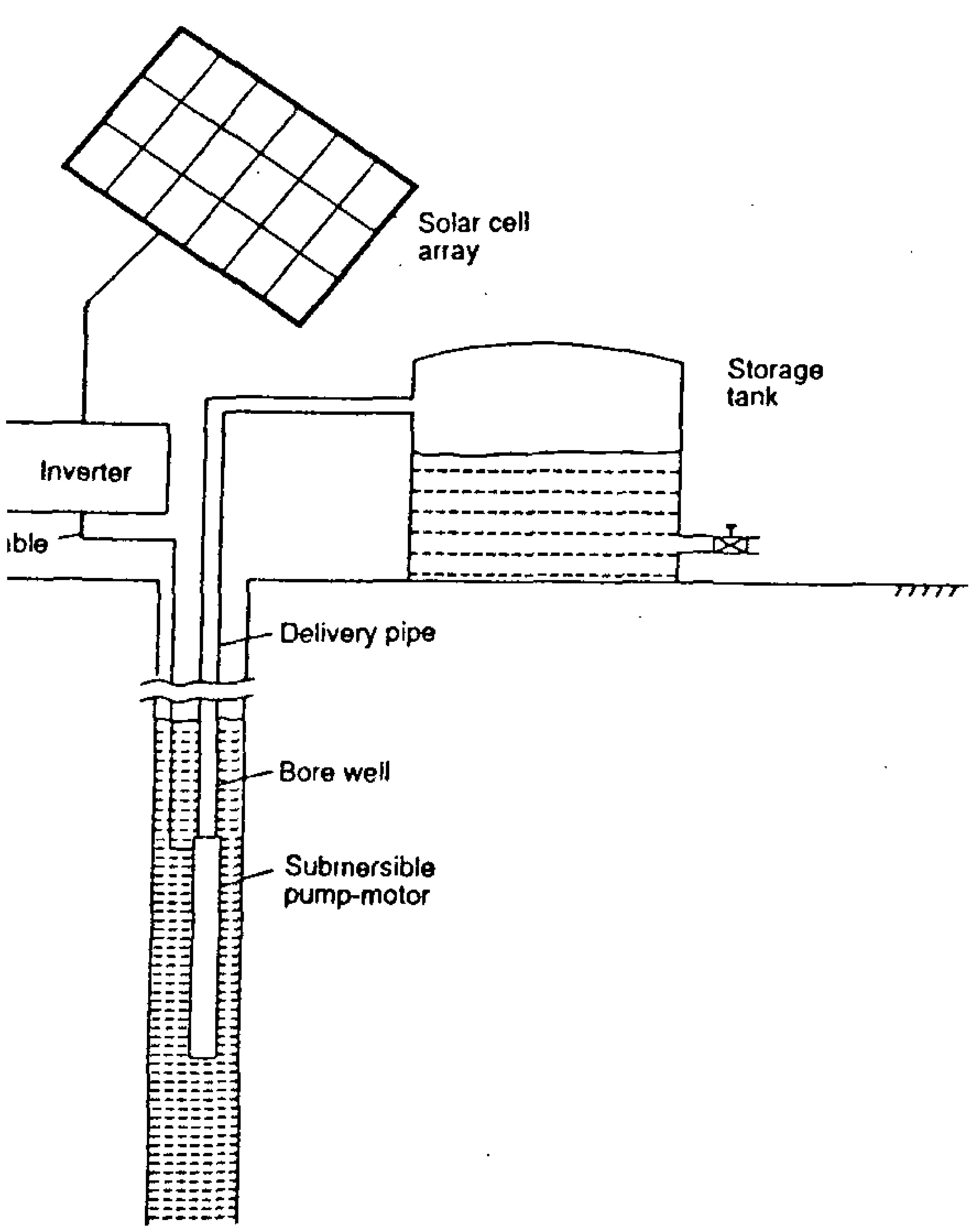

Figure 2. A photovoltaic water-pumping system.

Nineteen village level PV power packs of 113 kWp aggregate capacity have also been installed till June 1996 (ref. 1). The PV power packs comprise individual home lighting systems for each household, a few street lighting systems, a community TV system for education and entertainment and a community drinking water pumping system. A typical power pack has a capacity of about 10 kW peak and comprises 80 home lighting systems, 20 street lighting systems, two community TV systems and a community water pumping system. Such systems have been functioning satisfactorily for the last 5 years.

Most of these power packs have been installed in villages in Jaisalmer and Udaipur districts. Over the years, REDA has evolved a method for maintenance and servicing of these power packs with the active co-operation of the beneficiaries and system suppliers.

The Rajasthan Government has also proposed that 552 villages in the districts of Udaipur, Jaisalmer and Ganganagar be electrified with PV power packs. The above villages are not likely to be electrified by conventional grid power during the next 5–10 years. The aggregate PV capacity of these systems is about 1.44 MWp and the total cost is likely to be about Rs 66 crores.

Recently efforts are also being directed towards establishing and demonstrating the potential of solar photovoltaics to generate larger amounts of power which would supplement and augment grid power. MNES has completed two pilot village electrification projects of 100 kW each, with 25 kW grid connected components. The projects have provided initial insights for the design of high voltage systems, power conditioning unit, grid integration, etc. The Ministry is now in a position to demonstrate various grid-connected possibilities based on new design concepts and more such projects are planned. It is expected that higher conversion efficiencies and optimally engineered systems will bring about rapid market expansion, which will eventually lead to a decline of costs of PV systems. This stage is likely to be reached by the turn of the century when solar photovoltaics could approach competitiveness for grid-connected applications.

Keeping in mind the above developments, the Government of Rajasthan has issued Letters of Intent for the establishment of two large-sized PV solar power plants which would be connected to the grid. Both these plants have a capacity of 50 MW. One is based on PV thin film technology and the other on PV modules using concentrators. The plants are to be established on a build, own, operate and maintain (BOOM) basis and the commitment of the State Government is to buy the power generated from these plants at the following rates:

Rs 2.25 per unit for the first three years,
Rs 2.70 per unit for the fourth year,
Rs 3.82 per unit for the next seven years and

Rs 2.25 per unit for the remaining period up to 25 years.

Solar thermal power generation systems*

Solar thermal power systems can be classified as working on low, medium and high temperature cycles. Low-temperature cycles work at maximum temperatures of about 100°C, medium-temperature cycles work at maximum temperatures up to 400°C, while high-temperature cycles work at temperatures above 400°C (ref. 2).

Low-temperature systems use flat-plate collectors or solar ponds for collecting solar energy. Recently, systems working on the solar chimney concept have been suggested. Medium-temperature systems use the line focussing parabolic collector technology. High-temperature systems use either paraboloidal dish collectors or central receivers located at the top of towers.

Low-temperature systems

A diagram of a typical low-temperature system using flat-plate collectors and working on a Rankine cycle is shown in Figure 3. The energy of the sun is collected by water flowing through the array of flat-plate collectors. The hot water at temperatures close to 100°C is stored in a well-insulated thermal storage tank. From here, it flows through a vapour generator through which the working fluid of the Rankine cycle is also passed. The working fluid has a low boiling point. Consequently, vapour at about 90°C and a pressure of a few atmospheres leaves the vapour generator. This vapour then executes a regular Rankine cycle by flowing through a prime mover, a condenser and a liquid pump. The working fluids normally used are organic fluids like methyl chloride and toluene, and refrigerants like R-11, R-113 and R-114.

It has to be noted that the overall efficiency of this system is rather low, because the temperature difference between the vapour leaving the generator and the condensed liquid leaving condenser is small. For the cycle shown in Figure 3, the Rankine cycle efficiency is about 7–8%. The efficiency of the collector system is of the order of 25%. Hence an overall efficiency of only about 2% is obtained. Because of the low overall efficiency, large collector areas are required and such plants have been found to be very costly. Typically the installed cost is about Rs 300,000 per kW for 6 to 8 h of daily operation, the main component of cost being the collectors.

In order to reduce the cost, solar ponds have been used instead of flat-plate collectors. The first two solar pond power plants having capacities of 6 kWe and 150 kWe were constructed in Israel about 15 years ago. These were followed in 1984 by the Bet Ha-Arava power plant, the largest in the world with a capacity of 5 MW. The working of these plants has established the technical viability of solar pond power plants. However, they also do not appear to be economically attractive.

Recently the concept of a solar chimney power plant has been suggested. In such a plant, a tall central chimney is surrounded at its base by a circular greenhouse consisting of a transparent cover supported a few metres above the ground by a metal frame (Figure 4). Sunlight passing through the transparent cover causes the air

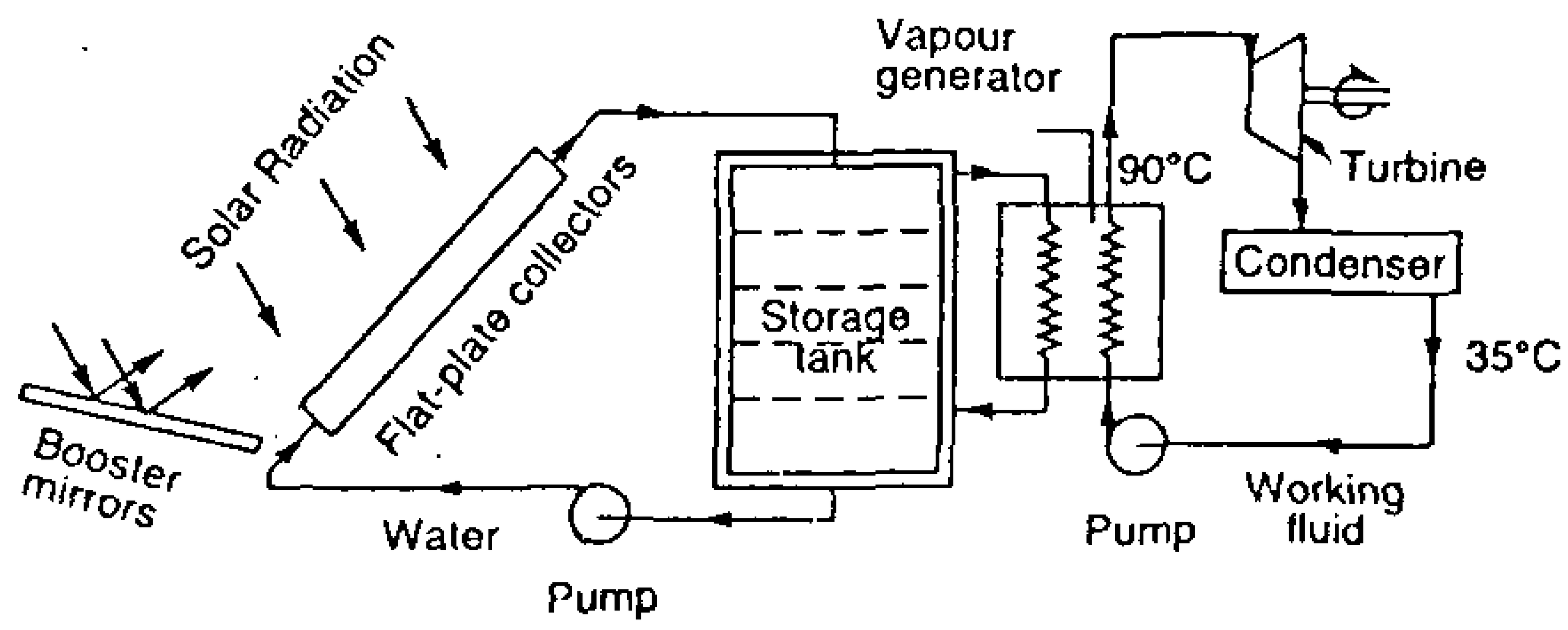

Figure 3. Low temperature power generation cycle using flat-plate collectors.

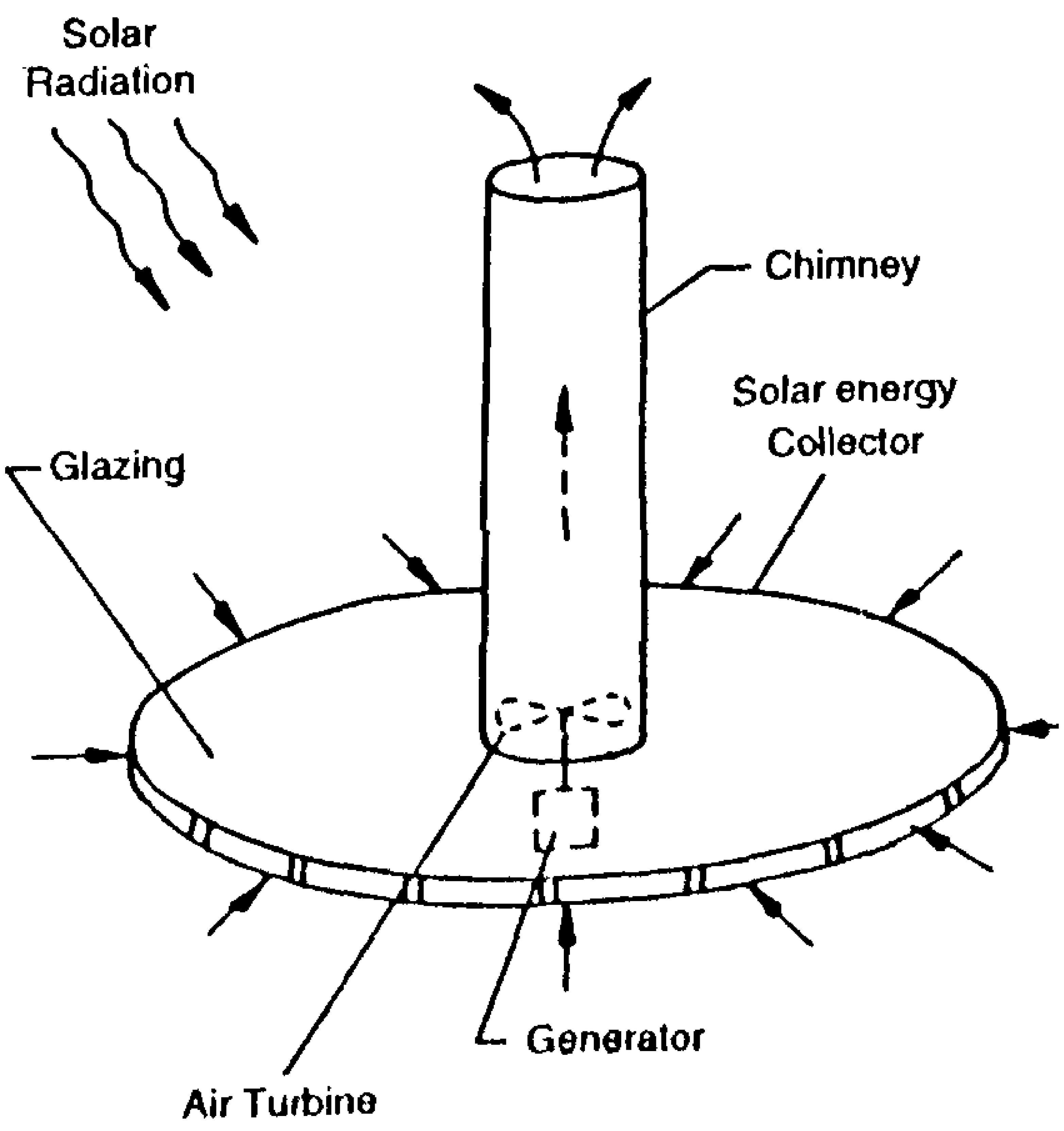

Figure 4. Solar chimney power plant.

*From a historical view point, it is of interest to note that the first experiments on the generation of solar thermal power in India were conducted by an Englishman, William Adams, more than one hundred years ago. Adams stayed in Mumbai and performed his experiments in the compound of his bungalow. He has described his work in a book entitled *Solar Heat – A Substitute for Fuel in Tropical Countries for Heating Steam Boilers and Other Purposes* (Education Society's Press, Byculla, Mumbai, 1878).

trapped in the greenhouse to heat up. A convection system is set up in which this air is drawn up through the central chimney turning a turbine located near the base of the chimney. The hot air is continuously replenished by fresh air drawn in at the periphery of the greenhouse.

The only solar chimney power plant built so far is a 50 kW pilot plant in Spain. It has a 200 m high chimney with a diameter of 10.3 m. The solar collector area extends to a radius of 126 m from the chimney with the glazing being 2 m above the ground. The turbine, housed at the base of the chimney, has four 5 m long blades and rotates at 1500 rpm to produce an output of 50 kW.

Although the energy conversion efficiency of such plants is low (less than 1%), it is claimed that there will be considerable reduction in cost with scale-up and that a large size 1000 MW plant may cost only about $ 1000 per kW.

Medium-temperature systems

Among solar thermal-electric power plants, those operating on medium-temperature cycles and using the line focussing parabolic collector technology at a temperature of about 400°C have proved to be the most cost effective and successful so far. A schematic diagram of a typical plant is shown in Figure 5. The first commercial plant of this type having a capacity of 14 MW was set up in 1984. Since then six plants of 30 MW capacity each, followed by two plants of 80 MW each have been installed and commissioned. All these plants have been set up in California, which has a total installed capacity of 354 MW. The collector array for the 80 MW plant has an area of 464,340 m^2. The cylindrical parabolic collectors used have their axes oriented north-south. The absorber tube used is made of steel and has a specially developed selective surface. It is surrounded by a glass cover with a vacuum. The collectors heat a synthetic oil to a temperature of 400°C with a collector efficiency of about 0.7 for beam radiation. The synthetic oil is used for generating superheated high pressure steam which executes a Rankine Cycle with an efficiency of 38%. The plant generally produces electricity for about 8 h a day and is coupled with natural gas for continuous operation. The installed cost of this type of plant has reduced over the years because of the increasing installed capacity. The latest 80 MW plant is reported to have cost $ 2900 per kW. The generating cost is about 8 cents per kWh.

The Indian experience with the line focussing parabolic collector technology has been restricted so far to a small

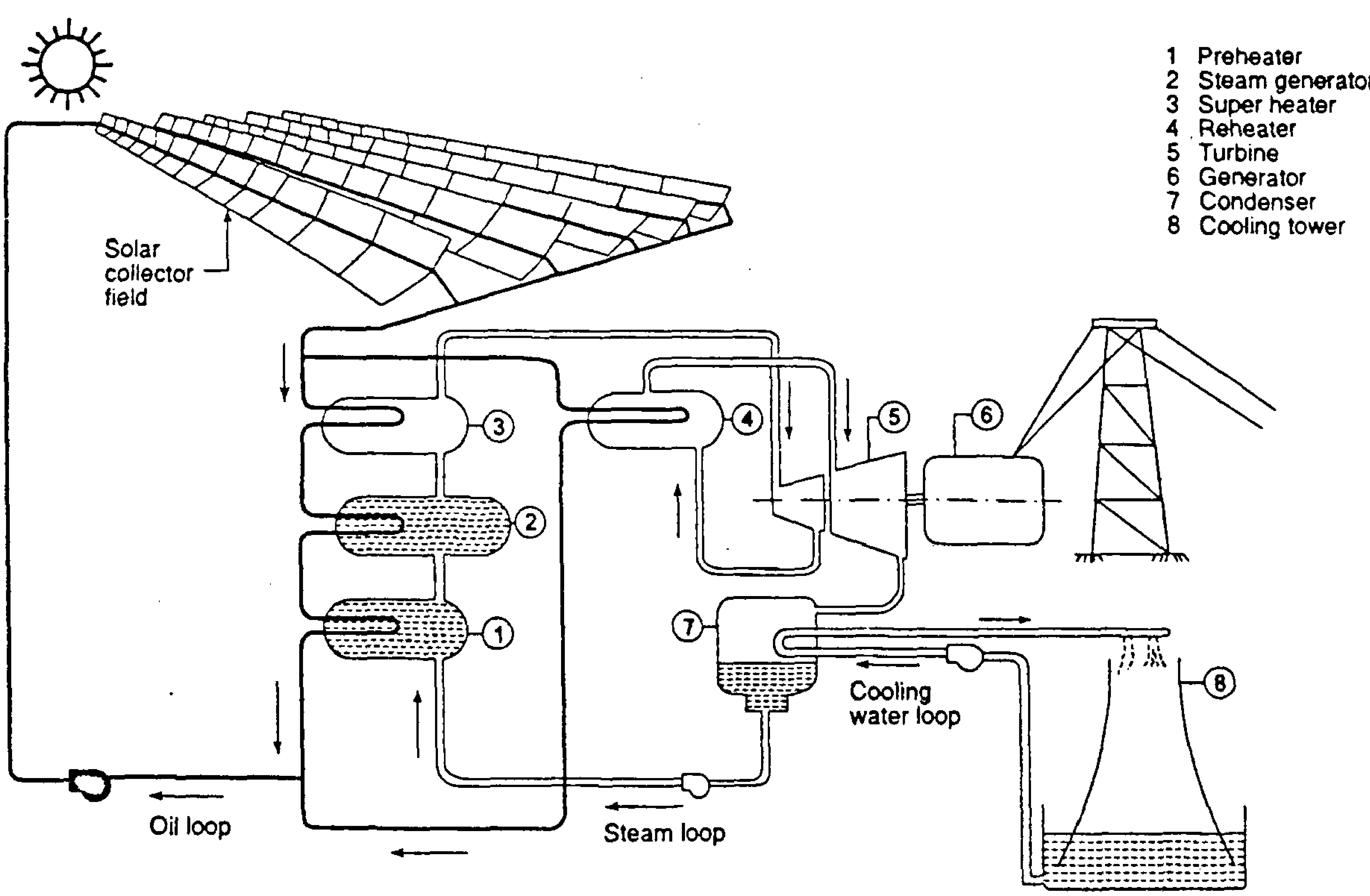

Figure 5. Medium temperature power generation cycle using parabolic concentrating collectors.

50 kW capacity experimental plant installed at the Solar Energy Centre near Delhi.

High-temperature systems

Two concepts have been tried with high-temperature systems. These are the paraboloidal dish concept and the central receiver concept.

In the paraboloidal dish concept, the concentrator tracks the sun by rotating about two axes and the sun's rays are brought to a point focus (Figure 6). A fluid flowing through a receiver at the focus is heated and this heat is used to drive a prime mover. Typically Stirling engines have been favoured as the prime movers and systems having efficiencies up to 30% and generating power in the range of 8 to 50 kWe have been developed.

The Indian experience with this type of system has been restricted to a small 20 kW power station near Hyderabad set up in the eighties. Four paraboloidal dish collector modules were used to generate steam which ran a steam engine.

Because of limitations on the size of concentrator, paraboloidal dish systems would generally be expected to generate power in kilowatts rather than megawatts. Thus they can only be expected to meet the local power needs of communities, particularly in rural areas.

In central receiver power plants, solar radiation reflected from arrays of large mirrors (called heliostats) is concentrated on a receiver situated at the top of a supporting tower. A fluid flowing through the receiver absorbs the concentrated radiation and transports it to the ground where it is used to operate a Rankine power cycle. A schematic diagram showing the main components of a central receiver power plant in which water is converted into steam in the receiver itself is shown in Figure 7. Alternatively the receiver is used to heat a liquid metal or a molten salt and this fluid is passed through a heat exchanger in which steam for the power cycle is generated. Seven central receiver power plants have been built in the eighties. All these plants were pilot plants and had outputs ranging from 0.5 to 10 MWe. A few details are given in Table 2. These include the number and the size of the heliostats, the receiver type, the receiver fluid and the height of the central supporting tower.

Although all the central receiver plants have been operated successfully, the available data indicate that the construction cost was very high. For example, the largest plant, Solar One, at Barstow, California cost approximately $ 14,000 per kW. However, costs are likely to reduce with more operational experience, improved design and scale-up.

Recently, Solar One has been converted from a water–steam system to a more advanced system using a molten salt. The molten salt at 290°C is pumped from a cold storage tank through the receiver where it is heated to 560°C, and then on to a hot storage tank. When electricity is to be generated, the hot salt is pumped to a steam-generating system that produces superheated steam for the turbine/generator. After giving up its heat, the salt

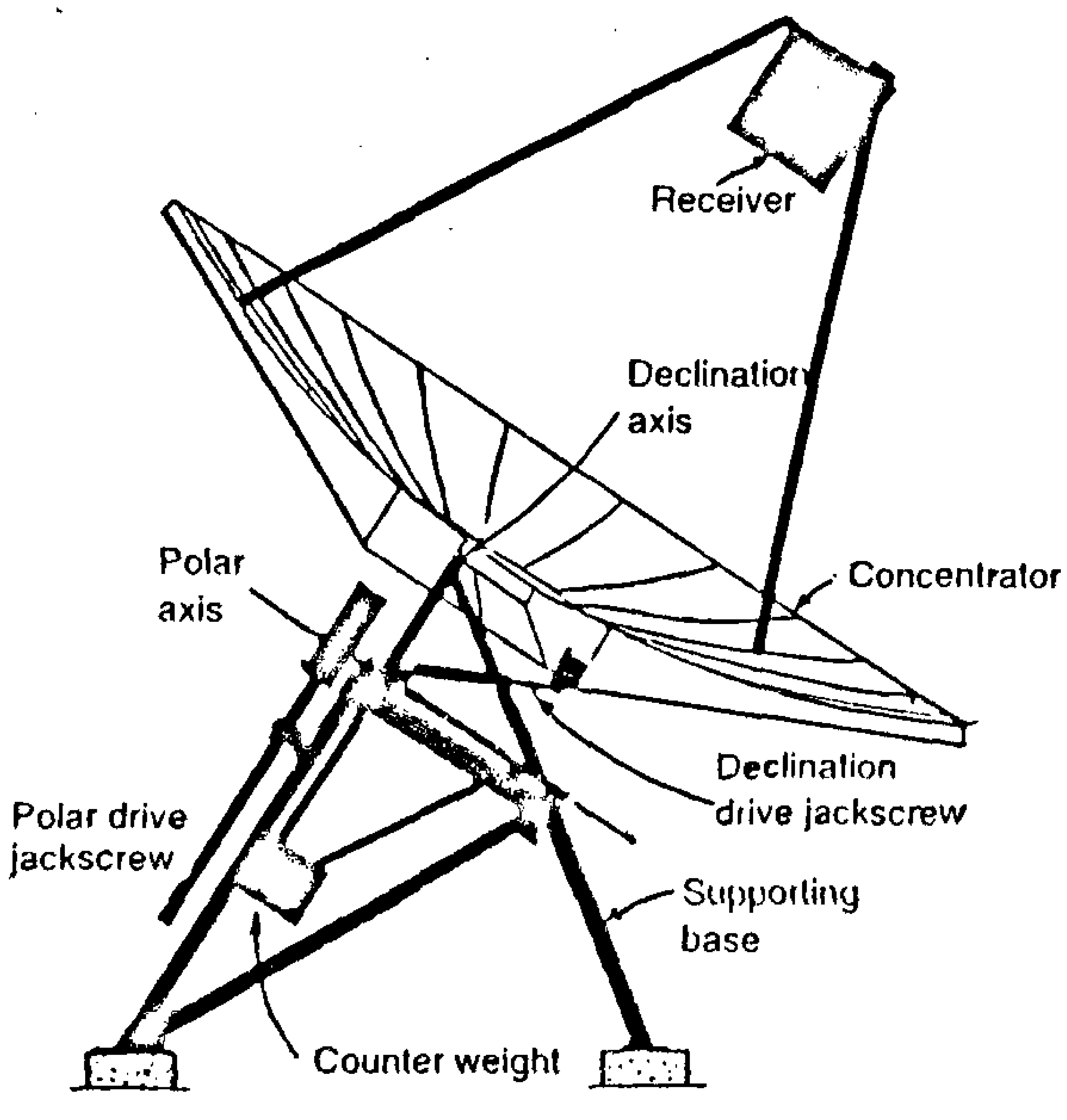

Figure 6. Paraboloid concentrating collector.

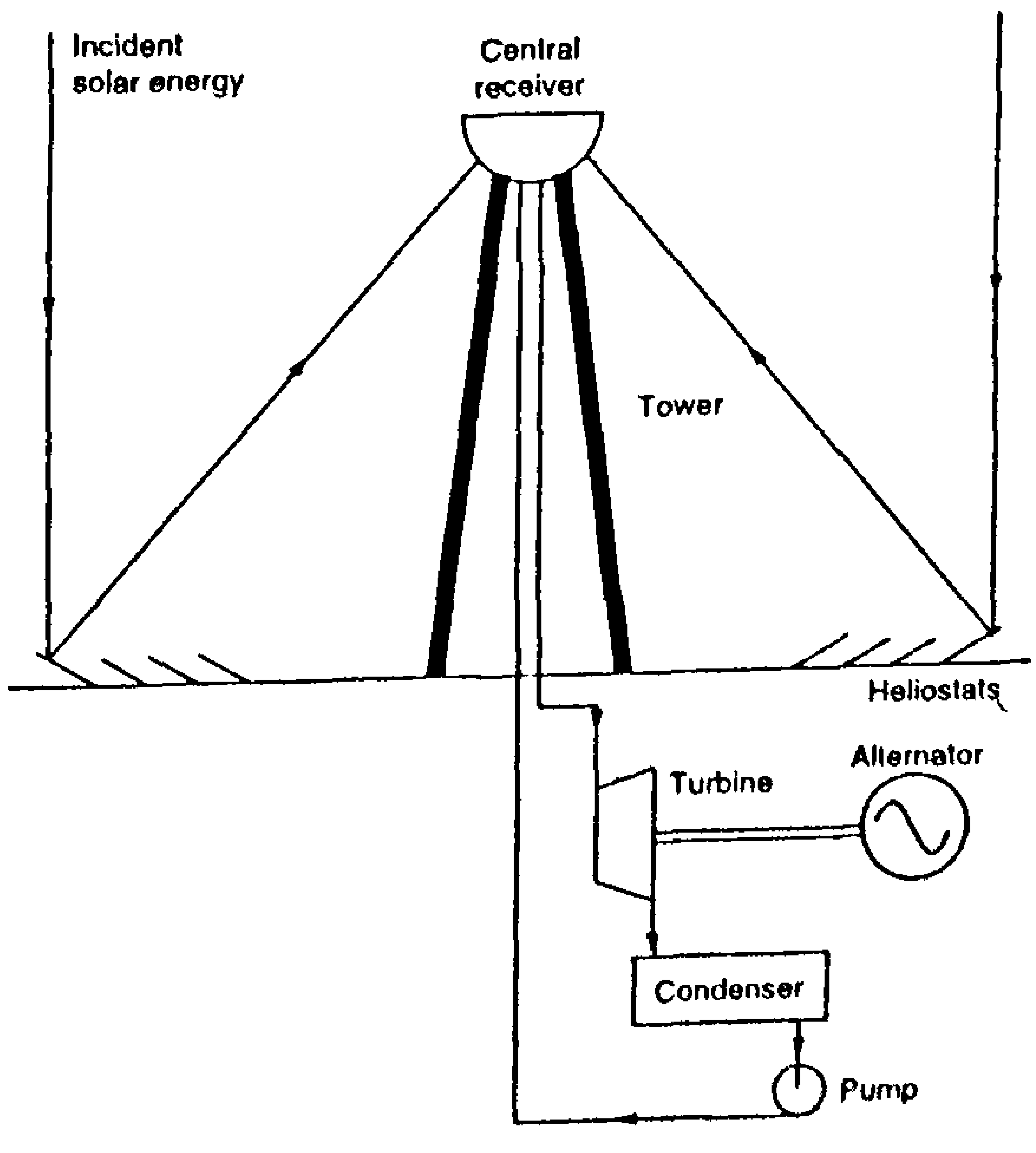

Figure 7. Central receiver power plant.

Table 2. Solar central receiver power plants[2]

Plant name	SSPS	Eurelios	CESA I	Sunshine	Themis	CES 5	Solar One
Location	Spain	Italy	Spain	Japan	France	USSR	USA
Output (MWe)	0.5	1	1.2	1	2	5	10
Number of heliostats	93	112,70	300	807	201	1600	1818
Area of heliostat (m^2)	39.3	23,52	39.6	16	53.7	25	39.3
Total reflecting area (m^2)	3655	6216	11880	12912	10740	40000	71447
Receiver type	Cavity	Cavity	Cavity	Cavity	Cavity	External	External
Receiver fluid	Sodium	Steam	Steam	Steam	Molten salt	Steam	Steam
Tower height (m)	43	55	60	69	–	70	80
Start of operation	1981	1981	1983	1981	1983	1985	1982

is returned to the cold storage tank. The converted plant, called Solar Two, began operation in June 1996 (ref. 3). It is expected that the use of molten salt will result in a higher efficiency and a better operating performance.

The Government of Rajasthan has also issued a Letter of Intent for a large 200 MW solar thermal power plant. The plant would be established on a BOOM basis and the State Government has made a commitment to purchase power at the same rates as for the two proposed 50 MW PV-based plants. The indications given are that the plant would be based on the solar chimney concept and located in Jaisalmer district. The plans are to construct the plant in stages with the chimney height as well as the collector area on the ground being increased in steps. The chimney would initially be 300 m in height, then raised to 600 m and finally to a height of 1000 m. The total collector area would finally be about 100 million m^2.

The other large power plant planned for Rajasthan is proposed to be located in Jodhpur district. It will be a 140 MW integrated solar combined cycle power plant with about 35 MW being generated from solar energy using the line focussing parabolic collector technology. The balance power of about 105 MW will be generated by conventional means using fossil fuels[1]. It is expected that this mix would be the most techno-economically feasible and viable option. A detailed feasibility report has been prepared and a laboratory established for collection of meteorological data at the selected site. Indications are that the total project cost may be of the order of $ 280 million. The mode of implementation, pattern of funding, and the role of various organizations are being finalized.

Concluding remarks

We have reviewed the state-of-the-art for generating solar electricity by the photovoltaic as well as the thermal route. As far as PV-based systems are concerned, the country has done well in developing indigenous technology and in setting up a large number of kilowatt scale power packs and systems for a variety of applications. Successful attempts have also been made to integrate these systems with the grid on the kilowatt scale. In so far as the thermal route is concerned, the domestic experience has been limited. However, an ambitious 140 MW integrated plant is planned for western Rajasthan. This should give the right impetus to the solar power generation programme.

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ACKNOWLEDGEMENTS. We are grateful to Shri Ajit K. Gupta, Dr E. V. R. Sastry, Dr Ahmar Raza and Dr B. M. S. Bist of the Ministry of Non-Conventional Energy Sources, Govt of India for providing valuable information and suggestions.